

## Anisotropic superconductivity in NbSe<sub>2</sub> probed by magnetic penetration depth

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### Abstract

NbSe<sub>2</sub> shows coexistence of a charge density wave ( $T_{\text{CDW}} \sim 32$  K) with a superconducting state below  $T = 7.2$  K. Recent ARPES measurements revealed different values of the superconducting gap on the main sheets of the Fermi surface. These results suggest a multigap superconductivity such as in MgB<sub>2</sub>. The temperature dependence of the magnetic penetration depth ( $\lambda(T)$ ) down to  $T_c/16$  has been measured on high quality single crystals in the Meissner state. A strong increase of the in-plane penetration depth is observed, signaling the presence of low lying excitations. Given the relative contributions of each Fermi surface sheet, these measurements indicate that a reduced gap is not necessarily only found on the small Se sheet as suggested by the ARPES measurements. These results are discussed in a framework of multigap superconductivity.

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The hexagonal dichalcogenides NbSe<sub>2</sub> has attracted a large interest in the last few decades for the coexistence of an incommensurate charge density wave with a superconducting state below  $T_c = 7.1$  K [1]. Furthermore, the superconducting state shows unusual properties, which can not be explained by an isotropic BCS weak coupling model. For example, the electronic specific heat has already shown the presence of a reduced energy gap [2]. Recently, NbSe<sub>2</sub> has been revisited in the light of multigap superconductivity. ARPES measurement suggested that the low energy excitation gap is due to the Se p-band which has a small electron–phonon coupling constant [3]. A directional probe combined to the particular anisotropy of the Fermi Surface of NbSe<sub>2</sub> allows us to test the excitation gap on the different sheets.

In this paper, we present high sensitivity measurements of the change of the in plane and *c*-axis temperature dependence of the magnetic penetration depth in the Meissner state (respectively  $\Delta\lambda_a$  and  $\Delta\lambda_c$ ). The detailed results are published elsewhere [4].

### 1. Experimental method

$\Delta\lambda_i$  ( $i = a$  or  $c$ ) was measured with a LC circuit driven by a tunnel diode operating at 14 MHz. The very low AC field probe ( $\sim 10$   $\mu$ T) and the screening of any DC magnetic field ensured that the sample was kept in the Meissner state. The frequency shift of the LC oscillator is directly proportional to  $\Delta\lambda$ .

Single crystals from three sources (Lausanne, Tsukuba, Bell Lab) have been measured in three different laboratories (Grenoble, Bristol, Urbana-Champaign respectively). Crystals of thickness  $t$  were grown with large flat layers

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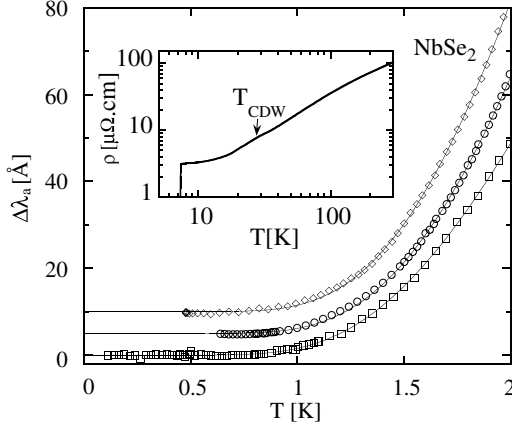


Fig. 1. Temperature dependence of the in-plane penetration depth for samples from different sources (measured at Bristol  $\square$ , Grenoble  $\circ$ , Urbana  $\diamond$ ). The field configuration is  $H\parallel c$  for Bristol's samples with an aspect ratio of 40. The contribution from the  $c$ -axis is negligible. For the other sample  $H$  is perpendicular to the  $c$ -axis. For clarity the data are offset. The lines are a fit with a superconducting gap of  $\Delta = 1.1 \pm kT_c$ . Inset, temperature dependence of the in plane resistivity for a single crystal from the same batch as Grenoble's samples.

perpendicular to the  $c$ -axis. Each side of the samples were cut. Samples from different batches have a RRR between 33 and 70 (see inset Fig. 1). No drastic change with sample quality has been observed.

When the magnetic field is applied along the  $c$ -axis, the supercurrents are flowing only in the basal plane. However, for a magnetic field applied perpendicular to the basal plane, both,  $a$  and  $c$ -axis directions are probed. For a sample of rectangular shape with a section ( $\perp H$ ) of width  $w$  and thickness  $t$ , the frequency shift is proportional to  $\Delta\lambda_a + \frac{t}{w}\Delta\lambda_c$ . To extract the out-of-plane penetration depth the aspect ratio of a sample is changed by cutting.

## 2. Results

In Fig. 1 the low temperature dependence of the in-plane penetration depth is shown. All the curves are fitted with the approximated expression (valid for  $kT < T_c/3$ ):

$$\Delta\lambda_i(T) \simeq \lambda_i(0) \sqrt{\frac{\pi\Delta_0}{2T}} \exp\left(-\frac{\Delta_0}{T}\right) \quad (1)$$

where  $\Delta_0$  is the superconducting gap at  $T = 0$  K. We find  $\Delta_0 = 1.1 \pm 0.1 kT_c$ , less than the value expected for a weak

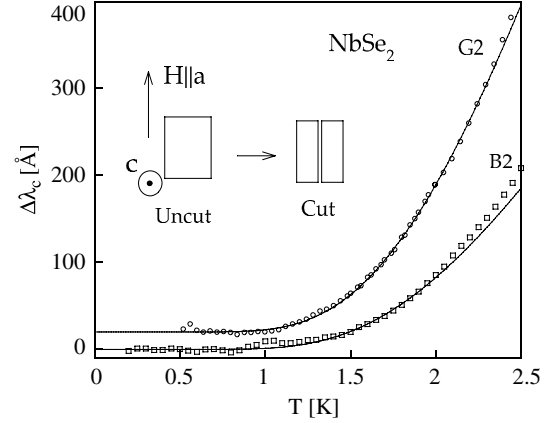


Fig. 2. Temperature dependence of the out-plane penetration depth calculated from a change of the aspect ratio (see text) (B2 measured at Bristol, G2 data from Grenoble is offset).

coupling BCS gap ( $\sim 1.76 kT_c$ ). In Fig. 2 the low temperature dependence of the  $c$ -axis penetration depth is fitted for  $T < 2$  K with the same expression. A gap of  $\Delta_0 = 1.3 \pm 0.1 kT_c$  is measured.

The experimental results have to be compared with the calculated Fermi surface. The Fermi surface of NbSe<sub>2</sub> is formed of two cylinders along the  $c$ -axis from the 4d-electrons of the Nb and also a small flat pancake around the center of the Brillouin zone from the p-electron of the Se. This sheet contributes only to 2% to the total in-plane superfluidity but 85% to the out-plane superfluidity [5]. So the reduced energy gap measured by in-plane penetration depth is on one or more of the quasi-2D Nb sheets. Moreover,  $\Delta\lambda_c$  shows that the superconducting gap associated to the Se sheet is not smaller than the smallest gap of the quasi-2D Nb band. These results are in strong contrast with previous measurements [3].

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